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The role of hand of error and stimulus orientation in the relationship between worry and error-related brain activity: Implications for theory and practice

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Abstract

Anxious apprehension/worry is associated with exaggerated error monitoring; however, the precise mechanisms underlying this relationship remain unclear. The current study tested the hypothesis that the worry-error monitoring relationship involves left-lateralized linguistic brain activity by examining the relationship between worry and error monitoring, indexed by the error-related negativity (ERN), as a function of hand of error (Experiment 1) and stimulus orientation (Experiment 2). Results revealed that worry was exclusively related to the ERN on right-handed errors committed by the linguistically dominant left hemisphere. Moreover, the right-hand ERN-worry relationship emerged only when stimuli were presented horizontally (known to activate verbal processes) but not vertically. Together, these findings suggest that the worry-ERN relationship involves left hemisphere verbal processing, elucidating a potential mechanism to explain error monitoring abnormalities in anxiety. Implications for theory and practice are discussed.

Descriptors: Worry, Anxiety, ERN, Verbal processing, Laterality

Anxious apprehension or worry is a distinct dimension of anxiety that is characterized by incessant concern for the future and verbal ruminations about negative outcomes (Barlow, 1991, 2002; Nitschke, Heller, Imig, McDonald, & Miller, 2001; Nitschke, Heller, Palmieri, & Miller, 1999). Neurologically, worry is associated with increased activity in a left-lateralized frontal network of brain regions thought to mediate language generation and cognitive control processes (Engels et al., 2007, 2010; Silton et al., 2011; Spielberg et al., 2013). This pattern of neural activation suggests that the effects of worry on everyday goal-directed behavior may be characterized by the interaction between excessive subvocal verbalization and the compensatory exertion of cognitive control in response to worry-related interference (Eysenck & Derakshan, 2011; Eysenck, Derakshan, Santos, & Calvo, 2007; Moser, Moran, Schroder, Donnellan, & Yeung, 2013; Warren et al., 2013).

One neurophysiological marker of cognitive control processes that may index this interplay is the error-related negativity (ERN), a negative deflection in the human ERP following the commission of an error (see Gehring, Liu, Orr, & Carp, 2012, for a review). Although still debated, the ERN is thought to reflect processes related to cognitive control such as early error correction (Yeung & Summerfield, 2012), conflict monitoring (Yeung, Botvinick, & Cohen, 2004; Yeung & Cohen, 2006), or reinforcement learning (Holroyd & Coles, 2002). The ERN is thought to be generated in medial prefrontal regions, including the anterior cingulate cortex (ACC) and the supplementary motor area (SMA; see Gehring et al., 2012, for a review).

Studies indicate that individuals with elevated symptoms of worry—including chronic worriers as well as those with generalized anxiety disorder (GAD) and obsessive-compulsive disorder (OCD)—exhibit increased ERN amplitudes on forced-choice tasks (Gehring, Himle, & Nisenson, 2000; Johannes et al., 2001; Weinberg, Klein, & Hajcak, 2012; Weinberg, Olvet, & Hajcak, 2010). It has been posited that the ERN may be exclusively related to worry because GAD and OCD are phenomenologically characterized by verbal ruminations. Indeed, Hajcak, McDonald, and Simons (2003) and Moser, Moran, and Jendrusina (2012) demonstrated that the ERN is modulated by worry but not anxious arousal—the physiological dimension of anxiety—indicating that worry may be uniquely related to exaggerated error-related brain mechanisms (see Moser et al., 2013, for a meta-analysis and review). Moreover, Zambrano-Vazquez and Allen (2014) provided further evidence for

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this specific relationship by showing that the exaggerated ERN present in OCD is primarily due to elevated worry.

Despite the growing evidence pointing to the specific relationship between worry and the ERN, the functional significance of this relationship is not well understood. However, Moser et al. (2013) recently proposed the compensatory error monitoring hypothesis (CEMH), suggesting that the enlarged ERN reflects compensatory post-error processing in response to worry-induced reductions in active goal maintenance. The theory is predicated on the notion that worry reduces the available capacity of the central executive system (Eysenck & Calvo, 1992; Eysenck & Derakshan, 2011; Eysenck et al., 2007). With attention diverted to off-task processes (i.e., worries), anxious individuals must compensate by putting forth more cognitive effort to maintain a standard level of performance. The enlarged ERN in anxiety is therefore considered to be a reflection of compensatory effort that subserves performance maintenance. This explanation accounts for the observation that, although anxious people exhibit increased ERNs relative to nonanxious people, there is typically no difference in performance accuracy on simple forced-choice tasks such as the flanker and Stroop tasks (Hajcak et al., 2003; Schroder & Moser, 2014; Vocat, Pourtois, & Viulleumier, 2008).

Consistent with the CEMH, higher levels of worry have been found to be associated with increased dACC activity (Silton et al., 2011) and reduced rACC activity (Bishop, Duncan, Brett, & Lawrence, 2004; Engels et al., 2007). This contrasting pattern of ACC activation suggests that worries may impede conflict resolution and proactive control processes, thus leading to the compensatory recruitment of cognitive control through reactive control processes (Braver, 2012). Given that a number of source localization studies have localized the ERN to medial prefrontal regions (Dehaene, Posner, & Tucker, 1994; Ullsperger & von Cramon, 2001; van Veen & Carter, 2002), the ERN-worry relationship likely involves overlapping control mechanisms that drive the aforementioned cognitive and behavioral disruptions associated with anxiety. Consequently, the present study aimed to advance the understanding of such mechanisms by exploring a potential nuance of the ERN-worry relationship: the role of verbal processing.

Studies show that worry is predominantly a verbal process, and that it is the verbal form of worry, rather than imagery-based worry, which depletes working memory and enhances attention to threatening information (Hayes, Hirsch, & Mathews, 2008; Leigh & Hirsch, 2011; Rapee, 1993; Williams, Mathews, & Hirsch, 2014). Demonstrating a clear relationship between verbal processes and worry, Engels et al. (2007) found that worry was associated with greater activity in the left inferior frontal gyrus—an area involved in subvocal articulatory rehearsal and maintenance of verbal information (Awh et al., 1996; Fletcher & Henson, 2001; Zatorre, Meyer, Gjedde, & Evans, 1996). Furthermore, recent research has highlighted the impact of verbal rumination on cognitive functioning; verbal worry delays processing of negative emotional stimuli and impairs the efficiency of inhibitory functioning (Spielberg et al., 2013; Warren et al., 2013). Given that (a) the ERN-anxiety relationship is primarily driven by worry, and (b) worry typically involves subvocal rehearsal, we propose that verbal processing may be an integral component of the ERN-worry relationship. Elucidating a link between verbal activity and the ERN-worry relationship would both provide support for and add specificity to a critical aspect of the CEMH—that the enlarged ERN observed in anxious individuals reflects the recruitment of reactive control in response to the depletion of on-task processing by task-irrelevant verbal processes. Such a link would suggest that the ERN-anxiety relationship is essentially a function of an automatized compensatory response to the impediments of off-task processing on active goal maintenance. In this study, we aimed to test this hypothesis through two experimental paradigms.

In the first experiment, we sought to determine whether the association between worry and the ERN differs between errors committed by the right and left hands. Because worry involves a strong linguistic component that is predominantly localized to the left hemisphere, we hypothesized that the ERN-worry relationship would be strongest for errors committed with the right hand, which is controlled by the left hemisphere. This approach is supported by substantial research into the relationship between lateralized neural functionality and hand motor activity. Lateralized dual task interference studies in conjunction with neuroimaging research have shown that right- and left-hand motor responses reliably activate the left and right hemisphere (e.g., motor regions), respectively, providing support for hands as a differentiating index of hemispheric activity (Ashton & McFarland, 1991; Chang & Hammond, 1987; Grefkes, Eickhoff, Nowak, Dafotakis, & Fink, 2008; Kinsbourne & Cook, 1971). Furthermore, performance monitoring ERPs have been shown to be sensitive to hemispheric manipulations such as selective stimulus presentation to the left or right visual field (Buchsbaum & Fedio, 1970; Mo, Xu, Kay, & Tan, 2011; Simon-Thomas, Role, & Knight, 2005).

Of particular relevance, transcranial magnetic stimulation (TMS) studies have shown that worry enhances motor preparation by increasing corticospinal excitability (Oathes, Bruce, & Nitschke, 2008), and that verbal processing alters the excitability of the left but not the right motor cortex (Buccino et al., 2005; Meister et al., 2003; Olivieri et al., 2004; Pullvermuller, Shtyrov, & Ilmoniemi, 2005). Moreover, a recent study by Hochman, Orr, and Gehring (2014) linked the ERN with motor processing, demonstrating that the ERN may be modulated by the differential potency between error and correct motor representations. Consequently, increased left motor cortex excitability may correspond to an enhanced potency differential for right-handed error responses and the generation of a bigger ERN. Taken together, these studies suggest that worry-related verbal processes may influence lateral motor execution—potentially increasing the likelihood of executing a right-hand motor response via enhanced excitability of the left motor cortex. Based on this theoretical foundation, we predicted that (a) the ERN elicited by right-handed mistakes, controlled by the linguistically dominant left hemisphere, would be more closely coupled with worry, and (b) that participants with higher levels of worry would commit more right-handed errors.

The second experiment served to complement the first by attempting to verify that the ERN-worry relationship is associated with verbal processing and not the neurophysiology of the dominant response hand. We aimed to accomplish this by manipulating the orientation of the flanker stimuli (horizontal vs. vertical presentation). The rationale for this design comes from studies examining the effects of stimulus orientation on lateralized linguistic processing (Jordan & Patching, 2003; Lindell, 2006; Lindell, Nichols, & Castles, 2003) and problem solving (Beilock, Rydell, & McConnell, 2007; Decaro, Rotar, Kendra, & Beilock, 2010; Trbovich & LeFevre, 2003). For instance, Lindell (2006) reviewed several studies showing the absence of a left hemisphere advantage for word recognition when words are presented vertically, suggesting a differential effect of stimulus orientation on the recruitment of lateralized linguistic processing. Specifically, horizontal stimuli appear to elicit more automized word recognition relative to vertical stimuli. The link between orientation and linguistic processing is further reinforced by studies that find a lateralized advantage for vertical stimuli from languages in which vertical presentation is culturally normative (Hellige & Yamauchi, 1999; Nakagawa & Sukigara, 2000). Moreover, Trbovich and LeFevre (2003) discovered that the orientation of stimuli impacts the type of resources used to solve problems. Solving horizontally presented arithmetic problems was mediated by verbal processes whereas solving vertically presented problems relied on spatial processing. Borrowing Trbovich and LeFevre's paradigm, Decaro et al. (2010) found that verbal worry compromised the ability to solve horizontal problems but not vertical problems, thereby highlighting a direct link between worry and stimulus orientation.

In summary, the first experiment sought to determine whether the ERN-worry relationship differed by hand of error, and the second experiment aimed to examine whether this relationship was dissociable by stimuli orientation. We reasoned that if verbal processing is left-lateralized, then right-handed ERNs should be more strongly correlated with worry relative to the left hand. Furthermore, if processing of horizontal stimuli is more linguistically mediated than vertical stimuli, we predicted that the ERN-worry relationship would be stronger on right-hand horizontal trials than vertical trials. Taken together, such findings would provide compelling evidence that the ERN-worry relationship is influenced by verbal processing.

Experiment 1

Method

Participants. Fifty-one female undergraduates participated in the study for course credit. We selected only females because the ERN is most strongly related to worry in females (Moran, Taylor, & Moser, 2012) and because women are twice as likely to suffer from an anxiety-related disorder (Kessler et al., 2005; Kessler, Petukhova, Sampson, Zaslavsky, & Wittchen, 2012). The sample consisted of 41 right-handed participants and 2 left-handed participants; 8 participants failed to report handedness. Handedness was assessed using a dichotomized single-item self-report measure (i.e., asking participants to indicate whether they were right- or left-handed). Nine participants were excluded from the analyses because of a failure to follow instructions regarding the stimulus-response mapping (see below) that resulted in an error rate exceeding 50% during one of the experimental blocks. The final sample consisted of 42 participants (33 right-handed, 2 left-handed, 7 unreported). Clinical disorders and medication use were not assessed. Participants ranged in age from 18 to 21 years ($M = 18.74$, $SD = 1.07$). No participants discontinued their involvement once beginning the experiment.

Task. Participants completed a letter version of the Eriksen flankers task (Eriksen & Eriksen, 1974). Participants were seated approximately 60 cm in front of a computer monitor and instructed to respond to the center letter of a five-letter string in which the target was either congruent (e.g., MMMMM or NNNNN) or incongruent (e.g., MMNMM or NNMNN) with the surrounding (i.e., flanking) letters. Characters were displayed in a standard white font on a black background and subtended 1.3° of visual angle vertically and 9.2° horizontally. The task was administered on a Pentium R Dual Core computer using E-Prime software (Psychology Software Tools, Inc.), which facilitated stimuli presentation and response measurement.

During each trial, flanking letters were presented 35 ms prior to target letter onset, after which all five letters remained on screen for an additional 100 ms (accumulating to 135 ms total trial time). Participants were given 1,000 ms to respond before the next intertrial interval began. A fixation cross (+) was presented during the intertrial interval, which varied from 1,200 ms to 1,700 ms. The experimental session included 480 trials grouped into 12 blocks of 40 trials. Participants were instructed to respond as quickly and as accurately as possible using either their left or right index finger to select the left (A) and right (L) keyboard buttons, respectively, which corresponded to the target identity. Letters making up the trial stimuli differed across block pairs: Blocks 1 and 2, M and N; Blocks 3 and 4, F and E; Blocks 5 and 6, O and Q; Blocks 7 and 8, T and I; Blocks 9 and 10, V and U; Blocks 11 and 12, P and R. Prior to each block, instructions regarding the specific target-button assignment were presented. Performance feedback was not provided.

Following the flanker task, participants completed a battery of self-report questionnaires including the Penn State Worry Questionnaire (PSWQ; Meyer, Miller, Metzger, & Borkovec, 1990) and the anxious arousal (AA) subscale of the Mood and Anxiety Symptom Questionnaire (MASQ; Watson & Clark, 1991). Borrowing from Nitschke et al. (2001), the PSWQ was used as a measure of anxious apprehension and the MASQ-AA was used as a measure of anxious arousal. The MASQ-AA was primarily included to test the specificity of the ERN relationship with worry (e.g., Moser et al., 2012).

Psychophysiological recording and data reduction. Participants were fitted with a 64-channel stretch-Lycra cap. Continuous electroencephalographic activity was recorded using the Active-Two BioSemi system (BioSemi, Amsterdam, The Netherlands). Recordings were taken from 64 Ag-AgCl electrodes placed in accordance with the 10/20 system. Two additional electrodes were placed on the left and right mastoids. Electrooculogram (EOG) activity generated by eye movements and blinks was recorded at FP1 and at three electrodes placed inferior to the left pupil and on the left and right outer canthi approximately 1 cm from the pupil. During data acquisition, the common mode sense active electrode and driven right leg passive electrode formed the ground, as per BioSemi's design specifications. All signals were digitized at 512 Hz using ActiView software (BioSemi).

Offline analyses were conducted using BrainVision Analyzer 2 (Brain Products, Gilching, Germany). Scalp electrode recordings were referenced to the numeric mean of the mastoids and bandpass filtered with cutoffs of 0.1 and 30 Hz (12 dB/oct rolloff). Ocular artifacts were corrected using the regression method developed by Gratton, Coles, and Donchin (1983). Physiological artifacts were detected using a computer-based algorithm such that trials in which the following criteria were met were rejected: a voltage step exceeding 50 μV between contiguous sampling points, a voltage difference of more than 200 μV within a trial, or a maximum voltage difference less than 0.5 μV within a trial. Trials were removed from ERP and behavioral analyses if the response time (RT) fell outside of a 200–800 ms time window. The response-locked data were segmented into individual epochs beginning 200 ms before response onset and continuing for 800 ms following the response. To quantify response-locked ERPs, the average activity in the 200-ms window preceding response onset was subtracted from each data point subsequent to the response. The ERN was then quantified as the average activity occurring between 0 and 100 ms

Table 1. *Summary of Behavioral and ERP Measures in Experiment 1*

	Overall		Left hand		Right hand	
Measure	M	SD	M	SD	M	SD
Error RT	372.89	42.14	438.01	37.67	425.50	34.34
Correct RT	438.28	34.94	444.41	37.29	432.41	34.42
Post-error RT	465.66	58.63	472.19	75.75	459.12	59.81
Postcorrect RT	435.84	34.13	442.13	36.15	429.55	33.71
Post-error slowing	29.82	40.95	30.07	62.68	29.57	41.08
Accuracy (% correct)	90.73	4.31	91.38	4.20	90.20	4.20
Number of errors	42.81	19.78	19.60	9.50	23.21	11.70
Post-error accuracy	87.57	13.37	88.09	14.30	87.45	13.57
Postcorrect accuracy	91.23	4.19	91.93	4.03	90.63	4.79
Post-error accuracy diff.	−3.66	13.57	−3.84	14.72	−3.18	13.63
ERN	−3.58	5.31	−3.72	7.01	−3.43	5.62
CRN	−0.07	4.31	−0.41	4.75	0.27	4.17

postresponse at the frontocentral recording site FCz—where the ERN was maximal.

Overview of analyses. Behavioral and ERP measures were statistically analyzed using SPSS software (Version 21.0). MASQ-AA scores were highly kurtotic ($z = 2.2$) and therefore transformed in order to normalize the distribution ($z = .69$). Behavioral data were submitted to repeated measures analyses of variance (ANOVAs). Number of errors was submitted to a one-way hand of error (right vs. left) ANOVA. Overall RTs were submitted to a 2 (Hand: right vs. left) × 2 (Accuracy: correct vs. error) ANOVA. Post-error adjustments were examined by submitting RT and accuracy following error and correct trials to separate 2 (Hand: right vs. left) × 2 (Response Type: post-error vs. postcorrect) ANOVAs. When significant interactions emerged, follow-up t tests were conducted to aid in the interpretation of results. Degrees of freedom varied slightly among the F tests because of performance variability (e.g., a participant making no left-handed errors is excluded from analyses involving hand of error). For ERP analyses, the ERN was submitted to a 2 (Hand: right vs. left) × 2 (Accuracy: correct vs. error) ANOVA. Partial eta squared (η_p^2) is reported as an estimate of effect size in ANOVA models, where .05 represents a small effect, .1 a medium effect, and .2 a large effect (Cohen, 1973). Separate correlational analyses examining associations between ERN and PSWQ and MASQ-AA scores were conducted to test the main hypotheses of the current investigation. Specifically, statistical contrasts between dependent correlations were calculated using Hotelling's t test. Correlation coefficients (i.e., rs) ranging from .1–.29 are considered small effects, rs ranging from .30–.49 medium effects, and rs greater than .50 large effects (Cohen, 1988).

Results

Descriptive statistics for behavioral and ERP measures for Experiment 1 are presented in Table 1. Additionally, behavioral analyses of congruency are presented in the online supporting information.

Performance measures. Overall flanker task accuracy was high (M percent correct = 90.73%, $SD = 4.31\%$). Participants made an average of 42.81 errors ($SD = 19.78$), with more right-handed errors ($M = 23.21$, $SD = 11.70$, range = 3–49) than left-handed errors ($M = 19.60$, $SD = 9.50$, range = 3–39, $F(1,41) = 8.75$, $p = .005$, $\eta_p^2 = .18$). Consistent with our prediction, correlational analysis showed that, as PSWQ scores increased, participants made more right-handed errors ($r = .33$, $p = .03$) but not more left-handed errors ($r = .19$, $p = .23$). MASQ-AA scores were not significantly correlated with accuracy in either hand ($r\text{s} < |.12|$, $p\text{s} > .41$).

The analysis of RTs revealed a main effect of accuracy, confirming faster RTs on error trials ($M = 372.89$, $SD = 42.14$) than on correct trials ($M = 438.28$, $SD = 34.94$, $F(1,41) = 163.70$, $p < .001$, $\eta_p^2 = .80$), consistent with a speed-accuracy trade-off. A main effect of hand revealed faster overall RTs with the right hand ($M = 425.50$, $SD = 34.34$) than the left hand ($M = 438.01$, $SD = 37.67$, $F(1,41) = 8.40$, $p = .006$, $\eta_p^2 = .17$). There was not a significant Hand × Accuracy interaction, $F(1,41) < 1$. Neither anxiety measure was significantly correlated with RTs ($r\text{s} < |.24|$, $p\text{s} > .12$).

Analysis of post-error RT replicated the post-error slowing (PES) effect such that correct responses were slower on trials after errors ($M = 465.66$, $SD = 58.63$) than after corrects ($M = 435.84$, $SD = 34.13$, $F(1,41) = 22.27$, $p < .001$, $\eta_p^2 = .35$). The Hand × Response Type interaction did not approach significance, however, $F(1,41) < 1$, indicating that PES did not differ by hand. PES, calculated as the difference between post-error correct RTs minus postcorrect correct RTs, across both hands were not correlated with any anxiety measure ($r\text{s} < |.19|$, $p\text{s} > .22$).

Post-error accuracy analysis revealed that participants were numerically, but not statistically, more accurate after correct responses (M percent correct = 91.23%, $SD = 4.19\%$) than after errors (M percent correct = 87.57%, $SD = 13.37\%$, $F(1,41) = 3.04$, $p = .09$, $\eta_p^2 = .07$). There was no main effect of hand on postresponse accuracy, however, $F(1,41) = 2.33$, $p = .13$, $\eta_p^2 = .05$, nor was there a significant Hand × Response Type interaction, $F(1,41) < 1$. Postaccuracy difference, calculated as the difference between post-error accuracy minus postcorrect accuracy, across both hands were not correlated with the anxiety measures ($r\text{s} < |.26|$, $p\text{s} > .09$).

ERN. As expected, the main effect of accuracy was significant, $F(1,41) = 14.63$, $p < .001$, $\eta_p^2 = .26$, indicating larger negativity on error trials compared to correct trials (see Figure 1). However, there was no main effect of hand, $F(1,41) < 1$, nor was there a significant Hand × Accuracy interaction, $F(1,41) < 1$.

Critical to the main aims of the current investigation, correlational analysis showed that, as hypothesized, higher PSWQ scores were only significantly associated with greater ERN on right-handed errors ($r = -.33$, $p = .04$) but not left-handed errors or correct responses in either hand ($r\text{s} < |.04|$, $p\text{s} > .78$; see Figure 2). Hotelling's t test revealed that the PSWQ-ERN correlation on right-handed error trials was significantly larger than that on left-handed error trials, $t(39) = -2.25$, $p = .03$, $d = .72$. Consistent with our previous work (Moser et al., 2012), MASQ-AA scores were not significantly correlated with ERNs or CRNs in either hand ($r\text{s} < |.19|$, $p\text{s} > .24$), indicating that the ERN was uniquely related to worry.

Discussion

Findings from Experiment 1 were consistent with our hypothesis that the ERN-worry relationship would be stronger for errors made with the right hand. Thus, these results provide support for our prediction that the ERN-worry relationship is associated with lateralized verbal activity. Also, as predicted, PSWQ scores were positively correlated with the number of right-handed errors but not

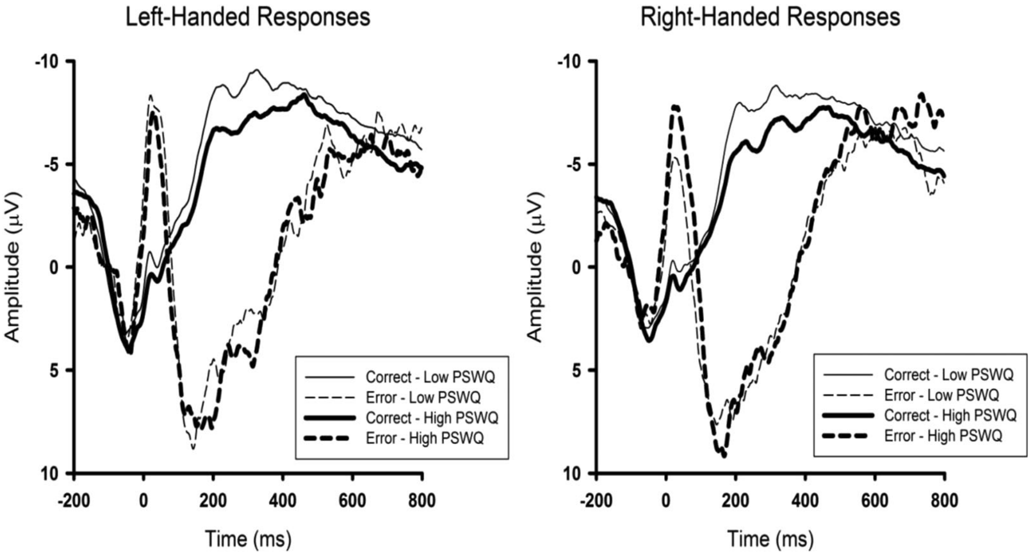

Figure 1. Response-locked ERPs plotted by accuracy and median-split PSWQ scores separated by hand of error at electrode site FCz.

left-handed errors. An in-depth discussion of these results will be reserved for General Discussion.

In Experiment 2, we sought to further explore the role of verbal processing in the ERN-worry relationship. First, we modified the orientation of the flanker stimuli to examine if the ERN elicited by the right hand would differ based on vertical or horizontal presentation. We hypothesized that since horizontal stimuli have been shown to recruit verbal processes, then the ERN-worry relationship should be stronger on horizontal trials; importantly, obtaining differential ERN-worry correlations based on orientation would provide compelling evidence to rule out the possibility that the ERN-worry relationship is driven solely by the neurophysiology of the right hand. Second, since right-handed individuals comprised the majority of the participants in Experiment 1, we recruited an equal number of left- and right-handed participants to rule out the likelihood that the results of Experiment 1 were merely a function of handedness—specifically, the possibility that worry simply enhances the error potency and subsequent response conflict in the dominant hand. Lastly, we replaced the letters comprising the flanker stimulus with arrows to reduce the verbal nature of the stimuli, thereby minimizing a potential confound that could interfere with the primary manipulation of interest (i.e., the effect of orientation).

Overall, the purpose of Experiment 2 was to strengthen our conceptualization by subjecting alternative interpretations of the results of Experiment 1 to falsification. Specifically, our predictions were that (a) the ERN-worry correlation would emerge on horizontal trials but not vertical trials, and (b) on horizontal trials, the ERN-worry relationship would only be present for right-handed errors but not left-handed errors—replicating the results of Experiment 1 with an equal number of right- and left-handed participants.

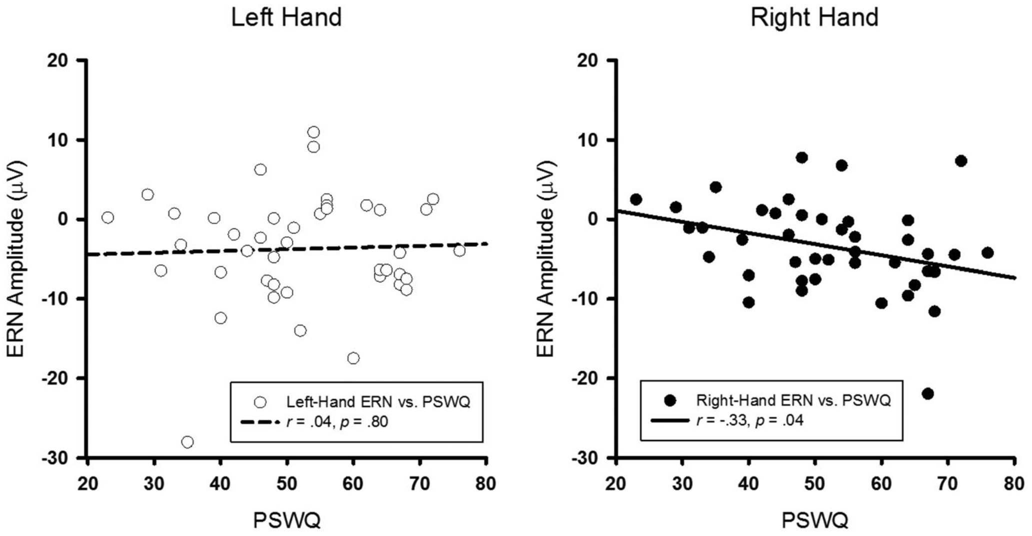

Figure 2. Scatter plots depicting the amplitude of the ERN as a function of PSWQ score and hand of error. There is a negative correlation between ERN and PSWQ for right-handed errors but not left-handed errors. As ERN scores are negative and PSWQ scores are positive, the negative correlation indicates that, as PSWQ score increases, so does ERN amplitude and vice versa. Removal of the participant in the lower right quadrant of the right scatter plot does not significantly affect the magnitude of the relationship between worry and right-handed ERN ($r = -.28$, $p = .08$).

Table 2. *Summary of Behavioral and ERP Measures in Experiment 2*

Measure	Overall		Left hand		Right hand	
	M	*SD*	*M*	*SD*	*M*	*SD*
Error RT: horizontal	350.40	38.05	348.84	49.44	349.68	42.76
Error RT: vertical	369.48	38.47	374.85	58.75	368.54	40.40
Correct RT: horizontal	421.04	43.20	418.59	44.36	423.77	43.17
Correct RT: vertical	439.15	43.67	440.78	46.11	437.98	43.05
Accuracy: horizontal	90.97	6.01	91.78	6.62	90.15	6.68
Accuracy: vertical	89.79	6.94	89.19	7.42	90.38	7.44
ERN: horizontal	−2.18	5.01	−2.36	5.92	−2.02	5.68
ERN: vertical	−3.49	6.09	−3.37	7.01	−3.60	6.39
CRN: horizontal	2.70	4.90	2.50	4.88	2.90	5.06
CRN: vertical	2.79	5.37	2.76	5.40	2.81	5.58

Experiment 2

Method

Participants. Seventy-four female undergraduates participated in the study for course credit. Per our recruitment strategy, the sample consisted of 37 right-handed participants and 37 left-handed participants. Similar to Experiment 1, handedness was assessed using a dichotomized single-item self-report measure (i.e., asking participants to indicate whether they were right- or left-handed). Three participants were excluded from analyses because of response-mapping errors that resulted in an error rate exceeding 50% across all trials. Two participants were excluded because of excessive movement during the task. The final study sample consisted of 69 participants (33 right-handed; 36 left-handed). Clinical disorders and medication use were not assessed. Participants ranged in age from 18 to 37 ($M = 19.49$, $SD = 2.49$), not differing significantly from the sample in Experiment 1, $t(98) = -1.70$, $p = .09$. No participants discontinued their involvement once beginning the experiment.

Participants completed an arrow version of the Eriksen flankers task (Eriksen & Eriksen, 1974). In contrast to Experiment 1, arrows were selected over letters to isolate the effect of spatial orientation. Participants were instructed to respond to the center arrow of a five-arrow array in which the target was either congruent (e.g., ⋙≫ or ⋘≪) or incongruent (e.g., ≫<≫ or ≪>≪) with the surrounding flanker arrows. Presentation of the arrows differed in orientation. On horizontal trials, equidistant arrows were presented horizontally at the center of the screen, whereas on verticals trials, the arrows appeared vertically with arrows pointing left or right. Arrows were displayed in a standard white font on a black background and subtended 1.3° of visual angle vertically and 9.2° horizontally for horizontal trials, and subtended approximately 9.2° of visual angle vertically and 1.3° horizontally for vertical trials. The task was administered on a Pentium R Dual Core computer using E-Prime software (Psychology Software Tools, Inc.).

During each trial, all five arrows were presented simultaneously for 100 ms. Participants had 900 ms to respond to the target before the response was deemed missing and excluded from data analysis. A fixation cross (+) was presented during the intertrial interval, which varied from 800 ms to 1,200 ms. The experimental session included 800 trials, consisting of 10 blocks of 40 horizontal trials and 10 blocks of 40 vertical trials. Orientation was randomized across blocks of the task, and incongruent and congruent trials were also randomized within each block. Using the keyboard, participants were instructed to respond by pressing the A (for a target <) or L (for a target >) keyboard button as quickly and as accurately as possible. Performance feedback was not provided.

Following the flankers task, participants completed a series of questionnaires including the PSWQ and MASQ-AA as in Experiment 1.

Psychophysiological recording and data reduction. The recording and data reduction procedures were identical to those described in Experiment 1.

Overview of analyses. As in Experiment 1, behavioral and ERP measures were statistically analyzed using rANOVAs. In contrast to Experiment 1, however, MASQ-AA scores did not exhibit skewness and kurtosis values greater than 2 and were not log transformed. Overall number of errors were submitted to a 2 (Hand: right vs. left) × 2 (Orientation: vertical vs. horizontal) repeated measures ANOVA. Overall RTs were submitted to a 2 (Hand: right vs. left) × 2 (Accuracy: correct vs. error) × 2 (Orientation: vertical vs. horizontal) ANOVA. Post-error adjustments were examined by submitting RT and accuracy following error and correct trials to separate 2 (Hand: right vs. left) × 2 (Response Type: post-error vs. postcorrect) × 2 (Orientation: vertical vs. horizontal) ANOVAs. When significant interactions emerged, follow-up *t* tests were conducted to aid in the interpretation of results. Partial eta squared (η_p^2) is reported as an estimate of effect size in ANOVA models. For ERP analyses, the ERN was submitted to a 2 (Hand: right vs. left) × 2 (Accuracy: correct vs. error) × 2 (Orientation: vertical vs. horizontal) ANOVA with handedness as a between-subjects factor. Critical to the main aims of the current investigation, separate correlational analyses examining associations between ERN and PSWQ and MASQ-AA scores were conducted. Statistical contrasts between dependent correlations were calculated using Hotelling's *t* test. Finally, follow-up analyses were conducted by combining horizontal trials from both experiments to examine the effects of handedness and experiment.

Results

Descriptive statistics for behavioral and ERP measures for Experiment 2 are presented in Table 2. Additionally, behavioral analyses of congruency are presented in the online supporting information.

Performance measures. Overall accuracy was high (M percent correct = 90.38%, $SD = 6.27\%$). The ANOVA revealed a main effect of orientation as participants made more errors on vertical trials ($M = 39.65$, $SD = 27.34$, range = 4–139) than on horizontal trials ($M = 34.81$, $SD = 23.52$, range = 5–104, $F(1,68) = 9.67$, $p = .003$, $\eta_p^2 = .13$). The main effect was qualified by a significant Hand × Orientation interaction, $F(1,68) = 21.49$, $p < .001$, $\eta_p^2 = .24$. Replicating the results of Experiment 1, follow-up analysis found that, on horizontal trials, there were more right-handed errors ($M = 19.10$, $SD = 13.13$, range = 1–56) than left-handed errors ($M = 15.71$, $SD = 12.79$, range = 2–58, $t(68) = 2.58$, $p = .01$). There was no significant difference in errors by hand on vertical trials (right hand: $M = 18.74$, $SD = 14.54$; left hand: $M = 20.91$, $SD = 14.64$, $t(68) = 1.77$, $p = .08$). There was no main effect of hand, $F(1,68) = .30$, $p = .59$, $\eta_p^2 < .01$. Neither anxiety measure was correlated with error rates ($rs < |.18|$, $ps > .16$).

A main effect of accuracy emerged on RT such that RTs on error trials ($M = 360.74$, $SD = 35.43$) were significantly faster than on correct trials ($M = 430.07$, $SD = 42.44$, $F(1,68) = 583.27$, $p < .001$, $\eta_p^2 = .90$). The ANOVA also revealed a main effect of

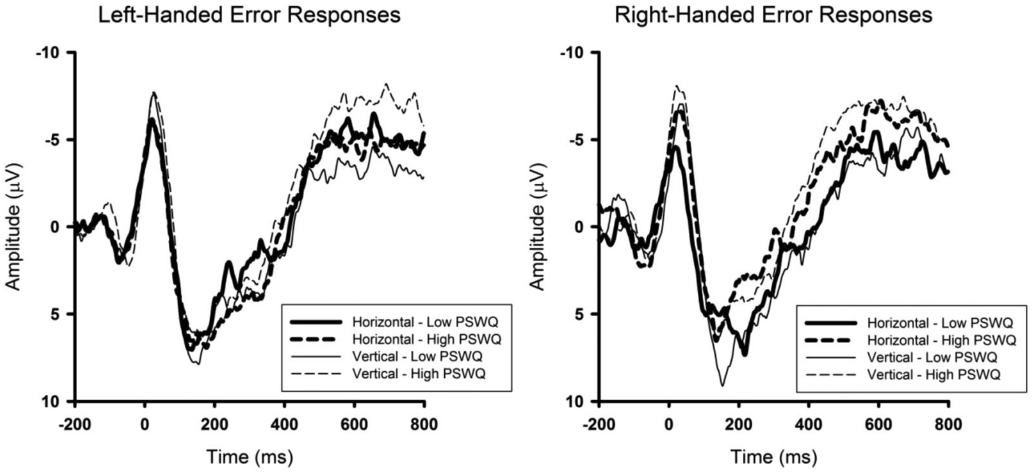

Figure 3. Response-locked ERPs plotted by stimulus orientation and median-split PSWQ scores separated by hand of error at electrode site FCz.

orientation, such that RTs on vertical trials ($M = 404.31$, $SD = 38.82$) were slower than horizontal trials ($M = 385.72$, $SD = 38.48$, $F(1,68) = 53.02$, $p < .001$, $\eta_p^2 = .44$). The main effect of orientation was qualified by a significant Hand × Orientation interaction, $F(1,68) = 6.63$, $p = .01$, $\eta_p^2 = .09$. Significant hand differences emerged only when comparing across different orientation (e.g., left horizontal RT vs. right vertical RT) due to slower overall RTs on vertical trials. There was no main effect of hand, $F(1,68) < 1$. No other significant interactions emerged (Fs < 1.37, ps $> .25$, η_p^2s $< .02$). Interestingly, correlational analyses showed that, as PSWQ scores increased, right-handed vertical error RTs increased ($r = .28$, $p = .02$). Correlations between PSWQ and other RTs were nonsignificant (rs $< |.19|$, ps $> .16$). MASQ-AA scores were not correlated with RTs (rs $< |.24|$, ps $> .14$).

A main effect of response type confirmed the PES effect; correct responses were slower on trials after errors ($M = 444.96$, $SD = 54.62$) than after corrects ($M = 426.3$, $SD = 42.02$, $F(1,67) = 38.49$, $p < .001$, $\eta_p^2 = .37$). There was also a main effect of orientation such that correct responses were slower on vertical trials ($M = 443.72$, $SD = 46.07$) than on horizontal trials ($M = 427.02$, $SD = 50.62$, $F(1,67) = 35.30$, $p < .001$, $\eta_p^2 = .35$), mimicking the overall slowing on vertical trials. There was no main effect of hand, $F(1,67) < 1$. There was neither an interaction between trial type and hand nor between trial type and orientation, Fs$(1,67) < 1$. PES, calculated as the difference between post-error correct RTs minus postcorrect correct RTs, was not correlated with any anxiety measure (rs $< |.19|$, ps $> .11$).

Overall, participants were not more accurate after errors (M percent correct = 90.90%, $SD = 9.71\%$) than after correct responses (M percent correct = 90.46%, $SD = 6.15\%$, $F(1,67) < 1$). There were no main effects of orientation, hand, or response type (Fs < 3.70, ps $> .06$, η_p^2s $< .05$). No significant interactions emerged for postresponse accuracy analyses (Fs < 3.48, ps $> .07$, η_p^2s $< .05$). There were no significant correlations between the anxiety measures and postresponse accuracy (rs $< |.21|$, ps $> .09$).

ERN. A 2 (Accuracy) × 2 (Orientation) × 2 (Hand) repeated measures ANOVA was conducted with handedness as a between-subjects factor. As expected, there was a main effect of accuracy, $F(1,65) = 83.84$, $p < .001$, $\eta_p^2 = .56$ such that the ERN was larger following errors than correct trials. There was also a main effect of orientation, $F(1,65) = 4.98$, $p = .03$, $\eta_p^2 = .07$, such that activity following vertical trials was more negative ($M = -.43$ $SD = 5.19$) than horizontal trials ($M = .19$, $SD = 4.28$, $t(67) = 2.31$, $p = .02$; see Figure 3). The main effects were qualified by an Accuracy × Orientation interaction, $F(1,65) = 6.61$, $p = .01$, $\eta_p^2 = .09$). The ERN was significantly larger on vertical error trials ($M = -3.65$, $SD = 6.20$) compared to horizontal error trials ($M = -2.32$, $SD = 5.11$, $t(68) = 2.78$, $p = .01$). There was no difference in CRN between vertical correct trials ($M = 2.68$, $SD = 5.40$) and horizontal correct trials ($M = 2.59$, $SD = 4.94$, $t(68) = .48$, $p = .64$). An unpredicted four-way Hand × Accuracy × Orientation × Handedness interaction also emerged, $F(1,65) = 4.84$, $p = .03$, $\eta_p^2 = .07$. We parsed this interaction by splitting the data by handedness. There was not a significant Hand × Accuracy × Orientation interaction in the right-handed participants, $F(1,31) = 1.78$, $p = .19$, $\eta_p^2 = .05$, but a marginally significant interaction emerged in the left-handed participants, $F(1,34) = 3.32$ $p = .08$, $\eta_p^2 = .09$. Consequently, we examined whether a differential interaction among accuracy, hand, and orientation would emerge for left-handed participants. No significant interactions emerged, (Fs < 1.45, ps $> .24$, η_p^2s $< .04$), and we concluded that the four-way interaction revealed no clear effects with respect to handedness on ERN modulation. No other significant differences emerged (Fs < 2.47, ps $> .12$, η_p^2s $< .04$).

Correlational analyses were supportive of our predictions. Analyzing Horizontal Trials × Hand revealed a differential relationship between the ERN and PSWQ. Consistent with our hypothesis and the results of Experiment 1, PSWQ scores were significantly correlated with the ERN on horizontal trials following right-handed errors ($r = -.35$, $p < .01$) but not left-handed errors ($r = -.15$, $p = .24$; see Figure 4). No significant relationships emerged for errors committed on vertical trials (rs $< |.13|$, ps $> .24$). Indeed, Hotelling's t test revealed a moderate difference between right- and left-handed ERN-worry correlations on horizontal trials, $t(66) = -1.80$, $p = .08$, $d = .44$, but not on vertical trials, $t(66) = .06$, $p = .95$, $d = .01$.

To examine the potential effects of handedness, we conducted separate correlational analyses in right- and left-handed participants. Although the horizontal right-hand ERN-PSWQ relationship was slightly attenuated in left-handed participants ($r = -.28$, $p = .09$) relative to right-handed participants ($r = -.42$, $p = .02$), Fisher's r-to-z transformation revealed that this difference was negligible ($z = .63$, $p = .53$). These null results suggest that handedness plays a minimal role in modulating the right-hand PSWQ-ERN relationship. MASQ-AA scores were not significantly correlated

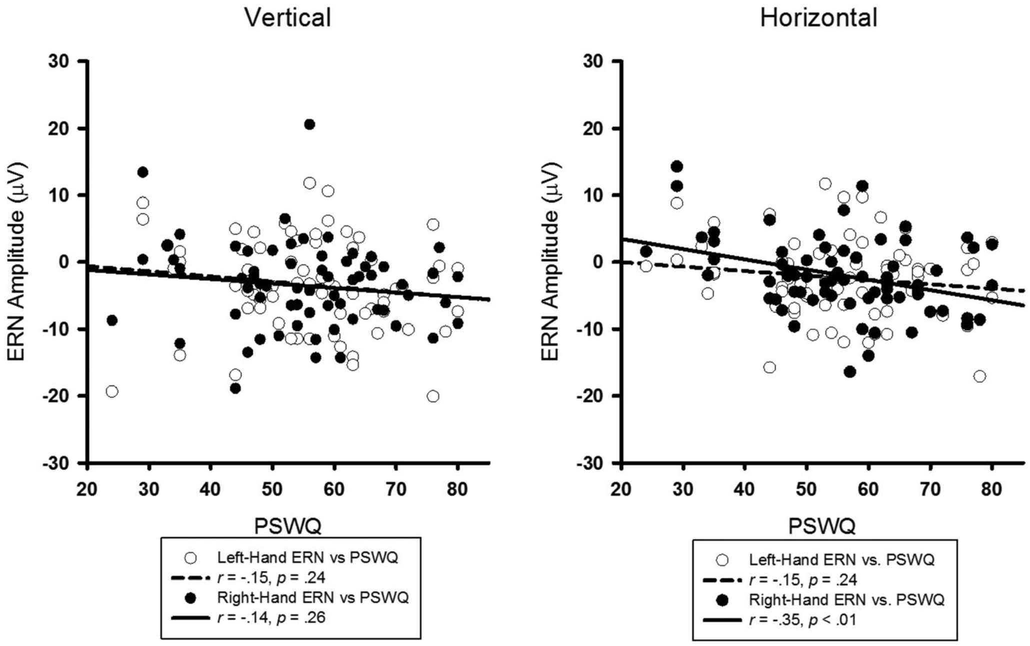

Figure 4. Scatter plots depicting the amplitude of the ERN as a function of PSWQ score, hand of error, and stimulus orientation. Replicating the results of Experiment 1, a negative correlation between ERN and PSWQ scores was found only on right-handed, horizontal trials. As ERN scores are negative and PSWQ scores are positive, the negative correlation indicates that, as PSWQ score increases, so does ERN amplitude and vice versa.

with any ERN (rs $< |.14|$, ps $> .26$). Neither PSWQ nor MASQ-AA scores were correlated with the CRN (rs $< |.12|$, ps $> .34$).

To the extent that an alpha of less than .05 represents a meaningful difference (Cumming, 2014), the absence of a statistically significant contrast between horizontal right-hand and left-hand ERN-PSWQ correlations was likely due to a lack of statistical power. Consequently, we combined the horizontal trial data from Experiment 1 and 2 ($N = 110$) and submitted the ERN to a single two-level within-subjects factor model (hand of error: right vs. left) with PSWQ scores entered simultaneously as a continuous predictor and experiment (Experiment: 1 vs. 2) as a between-subjects factor. As expected, the main effect of hand of error, $F(1,107) = 7.07$, $p < .01$, $\eta_p^2 = .06$, was qualified by a significant Hand of Error × PSWQ interaction, $F(1,107) = 6.81$, $p = .01$, $\eta_p^2 = .06$. Higher PSWQ scores were associated with bigger right-handed ERNs ($r = -.32$, $p < .01$) but not left-handed ERNs ($r = -.05$, $p = .59$; $t(107) = -2.83$, $p < .01$, $d = .55$). Critically, no other interactions emerged, including the Hand of Error × PSWQ × Experiment interaction (Fs $< .13$, ps $> .71$)—suggesting that experiment did not moderate the Hand of Error × PSWQ interaction.

To likewise examine the effect of handedness across studies, we repeated the analysis with handedness as a between-subjects factor. Again, the main effect of hand of error, $F(1,100) = 8.77$, $p < .01$, $\eta_p^2 = .08$, was qualified by a significant Hand of Error × PSWQ interaction, $F(1,100) = 7.00$, $p = .01$, $\eta_p^2 = .07$. Importantly, no other interactions emerged, including the Hand of Error × PSWQ × Handedness interaction (Fs < 1.76, ps $> .19$)—supporting the aforementioned correlational analysis that the right-hand ERN-PSWQ correlation was similar across left- and right-handed participants. Handedness was not a significant between-subjects factor, $F(1,100) = .60$, $p = .69$, $\eta_p^2 < .01$. Taken together, these results suggest that the differential ERN-PSWQ relationship by hand of error held across both experiments irrespective of specific paradigm or handedness.

Discussion

In line with our hypothesis, the ERN was most strongly correlated with PSWQ scores on horizontal error trials committed with the right hand. Moreover, we replicated the results of Experiment 1 after accounting for handedness, showing that the ERN-PSWQ relationship was exclusive to right-handed horizontal trials. A combined analysis of the horizontal trials showed that the right-hand ERN-PSWQ relationship held across both experiments and was not moderated by handedness. Together, these results provide initial evidence that verbal mechanisms play a role in the ERN-worry relationship.

General Discussion

Summary of Findings

The overarching goal of the study was to examine the role of verbal processing in the ERN-worry relationship through two experiments involving different tasks and participants. Based on evidence indicating that worry is associated with left frontal verbal brain activity, we predicted that the ERN-worry relationship would be largest on error trials committed with the right hand, which is controlled by the left hemisphere—demonstrating the significance of left hemispheric verbal processes in the worry-error monitoring relationship.

Across both experiments, the ERN-worry relationship differed by hand of error—that is, ERN and PSWQ scores were only significantly correlated on right-handed horizontal error trials. That the ERN-worry relationship was largest on horizontal error trials committed with the right hand is consistent with our prediction that the ERN-worry relationship involves left hemispheric verbal processing. Experiment 2 demonstrated that (a) the ERN elicited by right-handed mistakes on vertical trials was not significantly correlated with worry scores, and (b) the right-hand ERN-worry relationship on horizontal trials was not moderated by handedness. Critically, these findings are inconsistent with alternative hypotheses that the ERN-worry relationship is driven by the neurophysiology of the right hand or exclusively a function of the dominant response.

The finding that the ERN-worry correlation differed based on stimulus orientation is entirely consistent with research showing that verbal processes are recruited during presentation of horizontal stimuli but not vertical stimuli (Beilock et al., 2007; Decaro et al., 2010; Jordan & Patching, 2003; Lindell et al., 2003; Trbovich & LeFevre, 2003). Furthermore, the slight attenuation of the right-hand ERN-worry correlation in left-handed participants supports the involvement of left-hemispheric verbal processing given that a higher proportion of left-handed people (27% in strong left-handers relative to 4% in strong right-handers) exhibit right-hemisphere language dominance (Knecht et al., 2000). Replicating Moser and colleagues (2012), anxious arousal—as indexed by MASQ-AA scores—was unrelated to the ERN. Taken together, these results support the hypothesis that the anxiety-error monitoring relationship may be specific to verbal worry. In addition to advancing the specificity of the anxiety-error monitoring relationship, the present findings add a unique vantage point to a growing body of literature showing that left hemispheric verbal processing dissociates anxious apprehension from anxious arousal (Engels et al., 2007; Heller, Nitschke, Etienne, & Miller 1997; Hofmann et al., 2005; Nitschke et al., 1999).

Theoretical Significance

The functional model proposed by Hochman et al. (2014) offers a framework in which to elucidate the mechanistic underpinnings of our findings. Based on results from two novel ERN paradigms, Hochman and colleagues suggested that the ERN indexes processes dedicated to aborting an error. This conclusion follows from the parallel task set model (PTS, Seymour & Schumacher, 2009), which proposes that conflict occurs when a request to prepare a motor response differs from a request that is already in process. Specifically, this type of conflict occurs between prepotent unplanned errors and preplanned correct responses. The more prepotent the error representation, the more difficult it is to suppress the error response, and, consequently, the more likely it is that an error will be committed. Upon error commission, the preplanned correct response becomes corrective, and its automatized execution must wait until the error representation is suppressed. Consistent with the PTS model, Hochman et al. (2014) found that the wider the disparity between the prepotency of the error representation and the nonpotency of the correct representation, the larger the ERN. For example, they found that the ERN was larger when more errors were committed, presumably because the error potency was much stronger than the potency of the correct response.

With respect to the current findings, the observation that individuals with greater levels of worry exhibit greater right-hand ERNs suggests the possibility that worry serves to increase the prepotency of the right-hand motor response. In support of this notion, worry has been shown to be associated with greater corticospinal motor excitability, providing evidence that worry enhances motor preparation (Oathes et al., 2008). Moreover, evidence from the laterality literature suggests that the motor systems of the hemisphere controlling the dominant hand are more excitable and exhibit a lower motor response threshold relative to the nondominant hemisphere—in other words, the dominant hand is more prepotent (see Hammond, 2002, for a review). Given that the left hemisphere is dominant in approximately 90% of the population (Annett, 2004), it follows that, for a large majority of people, the right hand is more prepotent than the left. Consequently, if worry enhances motor preparation and the right hand is more prepotent than the left hand, then our findings suggest that worriers are more "prepared" to respond with the right hand relative to the left. Therefore, this enhanced prepotency would engender more right-handed "slips"—a type of error that, by definition, involves a wide error-correct potency disparity, and thus produces a larger ERN. Critically, we find that PSWQ scores were positively correlated with the number of right-handed errors in Experiment 1 where the majority of participants were right-handed, indicating that more worried individuals are indeed more likely to commit errors with the prepotent right hand.

The finding that the right-hand ERN-worry relationship was exclusive to horizontal trials and not moderated by handedness adds specificity to the hypothesis by showing that the prepotency of the right hand may be exacerbated by the verbal nature of worry—that is, recruitment of verbal processes in the linguistically dominant left hemisphere may "prime" the left motor cortex. This notion receives support from a number of TMS studies showing that processing action words or sentences alters the excitability of the left but not the right motor cortex and affects reaction times when the motor response and the verbal stimuli call the same effector (Olivieri et al., 2004; Buccino et al., 2005; Pulvermuller et al., 2005). More specific to the present findings, neurophysiological studies have found increased excitability in the hand motor area of the language dominant hemisphere during speech production, demonstrating a functional link between hand motor activity and language processing (Meister et al., 2003; Seyal, Mull, Bhullar, Ahmad, & Gage, 1999; Tokimura, Tokimura, Oliviero, Asakura, & Rothwell, 1996). Together, these studies reveal a unique interaction between the neural systems involved in motor action and language processing. Indeed, we found that, across both Experiment 1 and Experiment 2, there were significantly more right-handed errors than left-handed errors during the more verbally demanding horizontal trials but no difference on the spatially demanding vertical trials.

Although our findings appear consistent with the aforementioned literature, our hypothesis remains speculative due to the lack of empirical evidence demonstrating a direct link between subvocal rehearsal and enhanced motor excitability. A future study involving the manipulation of verbal working memory during the flanker task may offer a more direct way to evaluate our hypothesis. Indeed, a prior experiment in our lab supports the promise of such a design—we found that increased verbal working memory load was associated with a larger ERN and more errors (Moser et al., 2013). The caveat is, however, that all participants responded with their right hand using a mouse. Consequently, a future experimental manipulation involving lateralized response options (left vs. right) may be particularly fruitful. Moreover, employing a handedness inventory measuring handedness gradation (i.e., the extent to which one is left- or right-handed) rather than a dichotomized self-report may yield a more fine-grained analysis of the relationship between worry and motor potency.

Despite the substantial amount of evidence in support of our proposal, it is important to acknowledge the absence of a relationship between PSWQ and the number of right-handed errors in Experiment 2. The failure to replicate the effect of Experiment 1 may be attributed to differences in the complexity of the task design; that is, the enhanced cognitive load associated with frequent alternations between horizontal and vertical stimuli may have influenced the error rate. Furthermore, the use of arrows as the target stimuli may have reduced the verbal nature of the stimuli and thus diminished the priming effect of the left motor cortex. Lastly, the higher number of left-handed participants in Experiment 2 introduced more variability, as evidenced by the finding of an attenuated right-hand ERN-PSWQ in left-handed participants. As mentioned before, this attenuation is compatible with our conceptual model insofar as that left handers are less likely to be left-language dominant (Knecht et al., 2000). Additional empirical investigation will be needed to further validate our claims here. For instance, a worry induction paradigm using fMRI to differentiate left and right language dominance may help clarify the specific relationship among verbal worry, hemispheric dominance, and lateral motor execution.

Nonetheless, that we were able to link verbal activity with the ERN-worry relationship provides compelling support for a central aspect of the CEMH—that subvocal worries elicit disruptive off-task processing (e.g., increasing the probability of right-handed error slips through enhanced excitability) that trigger the engagement of reactive control (see Moser et al., 2013). Moreover, the present findings enrich the specificity of the CEMH, introducing the possibility that the interplay between verbally mediated worry and motor activity may constitute a key component of the ERN-worry relationship—that is, the enlarged ERN may reflect the extent to which the amount of processing required to abort the error (part of the broader error correction response) is modulated by worry-induced disparities between the potency of the correct and incorrect motor responses. In other words, worriers exhibit more error-corrective processing than their nonworried counterparts in order to maintain equivalent performance standards—a notion that is quintessential to the core principle of the CEMH model.

Practical Significance

There have been recent proposals to characterize the ERN as an endophenotype for internalizing disorders (Hajcak, 2012; Hajcak, Franklin, Foa, & Simons, 2008; Olvet & Hajcak, 2008). Specifically, the ERN is hypothesized to mediate the relationship between the genetic predisposition for affective disorders and their expression. Although some interpretations of extant research would lend credence to this proposal, our results argue against an unqualified interpretation of the ERN as a marker of affective disorders. By uncovering key moderators of the ERN-worry relationship, the current findings continue to illustrate the nuance and complexity underlying the link between the enhanced ERN and anxiety. Given the specificity of the ERN-worry relationship—that is, an enlarged ERN amplitude is most strongly correlated with worry (Moser et al., 2012) in women (Moran et al., 2012) on right-handed, horizontal error trials (data from the current study)—the ERN may not be a generalizable psychopathological risk factor. Rather, the predictive value of the ERN is most likely contingent on the moderators that uphold the relationship between the ERN and the construct of interest. Our data suggest that the ERN is most predictive of cognitive anxiety in females under task conditions in which stimuli are presented horizontally and errors are produced by the right hand—as it happens, a very common way that data have been collected in the literature to date (Hajcak et al., 2003; Moser, Hajcak, & Simons, 2005; Weinberg et al., 2010, 2012).

Conclusion

Through two experimental paradigms, the current study revealed the importance of verbal mechanisms in the relationship between worry and error processing. Uncovering moderators and mediators driving the impact of verbal worry on performance monitoring is likely to yield important theoretical and pragmatic insights for improving the understanding of the nature and impact of anxiety.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1: Behavioral analyses of congruency effects.